Analysis of Material Removal Rate and Surface Roughness on Advanced Ceramics Materials Micro-Hole Drilling

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***Abstract*-This study discussed the rotary ultrasonic machining (RUM) parameters and tool geometry parameters of optimized hole wall quality, and obtained better and uniformly distributed surface roughness of deep hole walls. The experimental configuration of this study was planned using Taguchi orthogonal array, where the hole diameter, spindle speed, feed rate and power were taken as the experimental factors. Drilling machining experiment was carried out using the parameter combination configured by the experimental design, and wall surface roughness of the drilled holes was measured. A relation model between the average surface roughness and standard deviation of the hole walls and processing parameters and tool geometry were established, so as to achieve optimized surface roughness of the overall deep hole walls. The optimization process respectively aimed at the minimum surface roughness and maximum metal removal rate. The experimental results proved that application of the optimized parameter combination in rotary ultrasonic machining of hole processing can obtain better and more uniform hole wall surface quality.The effect of control factors on the hole quality was discussed from the respects of the straightness deviation, minimum surface roughness and maximum metal removal rate of related factors on the hole when the Taguchi method was applied to rotary ultrasonic machining of hole drilling. The results showed that the level of straightness factors of produced holes can be fully presented.**

Keywords-Advanced Ceramics; Rotary Ultrasonic Machining; Surface Roughness; Material Removal Rate; Holes Deviation; Taguchi Method

I. INTRODUCTION

The Institute for Production Technology of University of Tokyo used Ultra Sonic Machining (USM) to drill 5μm-dia. micro-holes on hard brittle materials like glass, silica gel and ceramics. Wire Electrical Discharge Machining (WEDM) was first used to develop micro cylindrical tool on machining apparatus; then with machining apparatus working, 1μm-amplitude ultrasonic vibration occurred on the side of machining object; finally sub-micro diamond abrasive grains were utilized to control processing force. Therefore, the method can be used for micro hole drilling. WEDM is a method which may be applied to make micro tools, and enables such tools made on machining apparatus to adjust their central points automatically, so extremely low possibility of eccentricity could be ensured. The method is widely applied. Besides circular hole drilling and irregularly-shaped hole, it can also be employed for 3D shaped hole making.

In recent years, with industry manufacturing technology gradually advancing as product precision continually improving, more and more attention was attracted to management on product surface roughness in production site, inspection area, standard testing laboratory, research laboratory, etc. However, abrasion and lubrication caused by surface characteristics of work pieces in service, adhesive capacity of composition surface of work pieces, air-tightness and oil-tightness of sliding surface of work pieces, and surface finish exert direct and important influences on pursuing higher quality and better stability of the products in the industry. Take mechanical functions of work pieces for example, their surface structures are closely correlated with their performance; especially when work pieces are in contact with the surface of other work pieces, better smoothness is preferable; sometimes, however, some roughness is required. Therefore, to confirm mechanical performance of work pieces, surface roughness must be measured. The cutting process is an extensive manufacturing process in the industry. To improve product quality is absolutely one of the goals in all kinds of cutting operations, and machined surface roughness is also among important research topics relating to the quality of manufacturing process.

The vibration of cutting tool exerts important effect on hole shape. As for the researches in the respect, Sakuma et al. [1] (1980) found that vibration frequency was correlated with the number of machined hole corners by analysing the vibration frequency of cutting tool. Gessesse et al. [2] carried out processing tests of BTA deep holes under different spindle speeds, and observed the effect of processing parameters such as abrasion status of work piece material and cutting tool on spiral outline of hole shape. In 1992, Katsuki et al. [3] used gun drill and long twist drill to process work pieces with inclined plane, and discussed hole deviation. Experimental results showed that cutting force direction might affect hole deviation on inclined plane of work pieces; hole deviation caused by gun drill may go towards positive direction of horizontal axis and that caused by long twist drill towards negative position of horizontal axis. In 1990, Ei-Khabeery et al. [4] used experimental approaches and processing parameters like rotation speed, feed rate and hole diameter for processing experiment of deep holes with gun drill, and utilized surface roughness of hole wall discuss the influence of rotation speed, feed rate and hole diameter. Experimental results showed that better surface roughness of hole wall could be achieved with high rotation speed, low feed rate and small hole diameter. Although lots of scholars have researched processing of deep holes and quality of hole wall [4], [5], [6], these researches dealt with the quality of partial hole wall rather than whole hole wall.

This research mainly uses the experimental method to discuss the influence of RUSM on the whole quality of deep

hole in ceramics materials. In the process of machining, brittle failure (Micro scraps) is still dominating the removal mechanism of ceramics materials, if the machining parameters can't be controlled properly, it will cause poor roughness of the deeper subsurface crack. The analysis of this research consists of three parts: firstly, it analyses the integrity of ceramics materials in the process of RUM and the correlations between RUM and machining conditions through the results of axial sub-sectional measure in means and standard deviations of statistics; secondly, it discusses the machining parameters such as tool diameter, ultrasonic power density, speed of main shaft and feeding amount which are the keys to the research in the condition that grain size is fixed; finally, it discusses the influences of Taguchi quality experimental design method on machining quality with the expectation achieving better and more uniform surface quality of hole wall to ensure the hole quality after drilling and improve the machining rate.

experimental design and conditions

A. *Experimental Design and Conditions:*

This experiment is a precision test of RUM machining. Besides improving RUM technology and controlling the tolerance stably under 0.01mm, it also compares the precision testing methods of projection-type, optical microscopy true roundness, and profile testing method with each other. The experimental machine of RUM is of UMT-6 triaxial CNC ultrasonic wave, while the work piece materials is of ceramic glass (Zerodur), namely α (coefficient of thermal expansion of zero) of advanced glass material of which the physical property is showed in Table 1. This research initially adopts the Taguchi analysis and then consistently discusses the optimal profiling. RUM precision processing test is constructed by using rotary super ultrasonic processing machine for effects shown from main measurement tests including hole roughness, on the basis of the no. of fixed particle in diamond knife (#320) and the diameter of diamond knife (36μ~54μ), so four processing parameters are necessarily put into plans, which are knife diameter, machine power, main axle speed and feed rate.

TABLE1 PHYSICAL FEATURES OF CERAMIC GLASS

Density：2.53g/cm3
Heat capacity：0.80J/gK
Young's modulus：90.3Gpa
Knoop hardness：620

B. *Definition of Hole Precision and Testing Methods*

The hole precision can be divided into geometric diameters of true roughness, true straightness and parallelism of cylindricity tolerance and surface roughness. In addition, it also contains relative position tolerance of hole and other standard geometric shapes as plane and column, and true position degrees. The instructions of precision measurement instruments are as follows:

(1) Hommelwerke test T surface finish measuring instruments: Among the methods of expressing surface roughness, the average roughness in central line Ra is used most. This study will express surface roughness of hole wall by Ra value.

The average roughness value in central line is used most among all expression methods of roughness, which is defined as: A measurement length L is taken from curve surface of working piece where surface roughness exists, and the average height of length L is set up as x axle of central line, and vertical direction X is y axle, seen in fig. 1.

The average roughness of central line is expressed by equation:

$$R_a = \frac{1}{L}\int_0^L \left|f(x)\right|dx \tag{1}$$

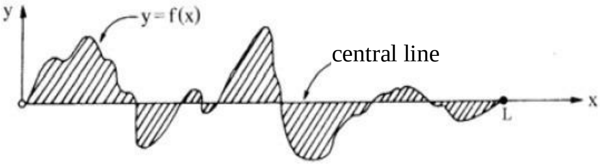

Fig. 1 Average roughness diagram of central line

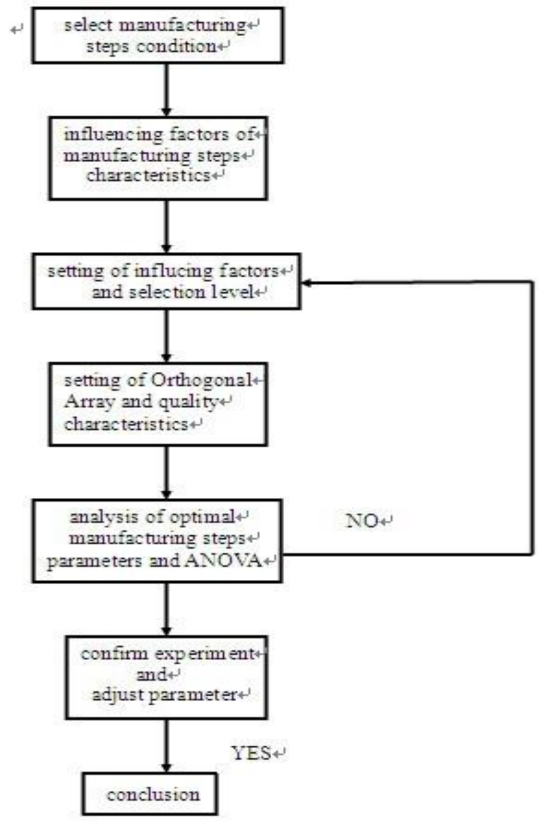

Fig. 2 Experimental flow chart of manufacturing steps

(2) Two-Coordinate Measuring Microscope (ZKM 01-250C): The main functions are to measure rectangular coordinates, polar coordinates, and column coordinates, and it also can be used in the distance measurement between two surfaces of plane and curve, and point, angle and axis. It is also used to measure the straightness, parallelism and square trowel.

(3) Calculation method of material removal rate:

According to [28] the following equation is used to calculate the material removal rate by diameter of hole after drilling, drill diameter and the time of drill punching through the work piece(d)

$$MRR = [\pi\, [\, (Dout/2)2 - (Din/2)2]\ \times d]\ \div T$$

Where

Dout: the diameter of hole after drilling

Din: the drill diameter

d: the thickness of work piece (40 ㎜)

T: the time of drill punching through the work piece thickness (d)

TABLE 2 EXPERIMENTAL CONFIGURATION

Code	Factor Name	Level 1	Level 2	Level 3
A	Diameter of drill bit (mm)	1	1.5	2.3
B	Rotation speed (RPM)	4000	4500	5000
C	Power	19	20	21
D	Feed rate	0.4	1	1.6

C. Design Variable of Taguchi Method and Level Meter

In drilling, hole quality is generally decided by surface roughness. The experiment uses Taguchi Method to plan the conditions for cutting experiment, and applies RUSM as cutting tool. The experiment is done in three steps: first, four experimental parameters are chosen based on surface roughness affecting cutting operation, i.e. diameter of drill bit, rotation speed, feed rate and power, as shown in Table 2; second, three level values are given to each experimental parameter, and 9 groups of tests are carried out according to Orthogonal Array (OA) of L9 (32) chosen; third, mean value of Taguchi Method is used for analysis, and the characteristics of surface roughness of target function are converted into Signal Noise Ratio (S/N).

$$S / N = -10 \times \log_{10} \left(\frac{1}{n} \sum_{i=1}^{n} y_i^2\right) \quad (2)$$

where S denotes standard deviation, which is defined as follows:

$$S = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \overline{y})^2}{n - 1}}$$

Experimental parameters are assessed according to the formulae above, and the parameter with greatest effect on surface roughness is diameter of drill bit, followed by rotation speed, feed rate and power. The experiment is designed to obtain average and correctness and planned into OA of L9 (32), totally with 9 groups of experiments involved, so as to improve experimental accuracy. Experimental flow chart of manufacturing steps is given in Fig. 2, and design steps of experimental parameters in Fig. 3.

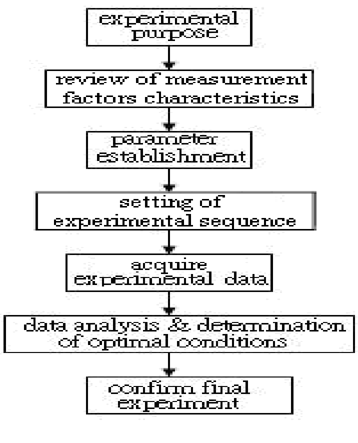

Fig. 3 Design steps of experimental parameters

II. RESULT AND DISCUSSION

Hole drilling on ceramic material is different from processing general metal materials. The quality of hole drilling, which is very important, is generally assessed by comparative analysis of roughness, roundness and parallelism etc. The process parameters affecting the roughness of hole include spindle speed, feed rate and ultrasonic power.

Many related works have compared the ultrasonic machining [7, 8] and rotary ultrasonic machining, such as the experimental data of brittle materials in respect of the main spindle speed, with the conclusion that the material removal rate (MRR) increased with the increase of circumferential speed of drilling bit [10, 11]. This experiment fixes diamond tool particle number (#320) and the diamond particle diameter (36μ~54μ) and varies the four machining parameters, including diameter of drill, rotation speed, power, and feed rate, to discuss their impacts on the roughness. The diameter of drilled hole is obtained through referring to the data measured by surface roughness tester and two-coordinate measuring microscope (ZKM 01-250 C) and making analysis based on the following conditions:

A. Optimization Analysis of Boring Parameters of RUM

According to the results of boring data, the relationship and framework of surface roughness and boring parameters are discussed for getting the optimum boring parameters and framework of surface roughness combination on the maximum MRR and minimal roughness of ceramic materials. The MRR experiment utilizes the LTB (larger the better) characteristics to carry out S/N ratio and plots the results as Table 3 and Fig. 4. In addition, the surface roughness experiment employs the STB (smaller the better) characteristics for S/N ratio and plots the results as Table 5 and Fig. 5.

1) MRR Analysis

According to the results of boring data, the relationship is discussed for getting the optimal boring parameter combined with the maximum MRR of ceramic materials. The MRR experiment utilizes the LTB (larger the better) characteristics to carry out S/N ratio and plots the results as Table 3 and Fig. 4. The contribution on MRR of every factor is shown in Table 4.

For boring and machining of ceramic materials as presented in Table 3, with drill diameter, rotation speed, power and feed rate of different cuttings, as well as fixed diamond tool particle number (#320) and diamond particle diameter (36μ~54μ), if the diameter is the same, the larger the rotation speed, power and feed rate are, the bigger the MRR is. As presented in Table 3, there is a large MRR (0.19154 mm3/min) with the drill diameter (ψ1.5), the rotation speed (5000RPM), the power (21) and the feed rate (1.6). For the same drill diameter (ψ1.5), the sub-rotation speed (4500RPM), the sub-power (20) and the sub-feed rate (1.0), the MRR is still large(0.1121mm3/min). Thus, for a fixed diameter of drill, the large rotation speed, power and feed rate still have a large MRR, as shown in Table 3.

Analysis of variance (ANOVA) can give more objective judgment on the relative effects between different factors. The table 4 is the ANOVA table for this process. The larger the F value is, the more important the factor for the MRR is. From Table 4 we know, the contributions of the factors are in the order as: rotation speed>diameter of drill >feed rate> power.

The reason is stated as below, the diamond particles of tools with a fixed drill diameter are the same, so when the MRR is considered only, in the scope of this experimental configuration seen as Table 2, the increase of rotation speed provides higher probability for diamond particle to contact, grind and machining workpieces, and consequently the impact of rotation speed is higher than that of other parameters (diameter of drill, feed rate and power).

Therefore, we obtain the optimum machining parameter A1B1C1D3 presented as Fig. 4. This indicates that diameter of drill (ψ1), rotation speed (4000) , power (19) and feed rate (1.6) can get the optimum MRR.

TABLE 3 MRR AUXILIARY TABLE

Sequence	A Diameter of Drill Bit	B Rotation Speed	C Power	D Feed Rate	MRR (mm^3/min)
1	1	4000	19	0.4	0.0102
2	1	4500	20	1.0	0.03813
3	1	5000	21	1.6	0.0558
4	1.5	4000	19	0.4	0.02151
5	1.5	4500	20	1.0	0.1121
6	1.5	5000	21	1.6	0.19154
7	2.3	4000	19	0.4	0.014455
8	2.3	4500	20	1.0	0.020828
9	2.3	5000	21	1.6	0.07532

TABLE 4 ANOVA TABLE

Factors	1	2	3	DOF	SS	SMS	F	Contribution
Diameter	31.09	22.23663	30.96	2	154.54	77.27	4.0047633	26.465
Rotation Speed	36.658	27.0032001	20.63	2	390.83	195.4	10.127814	66.927
Power	29.27	28.0612165	26.96	2	8.0213	4.011	0.2078592	1.3736
Feed Rate	27.099	26.5097041	30.68	2	30.569	15.28	0.7921408	5.2347

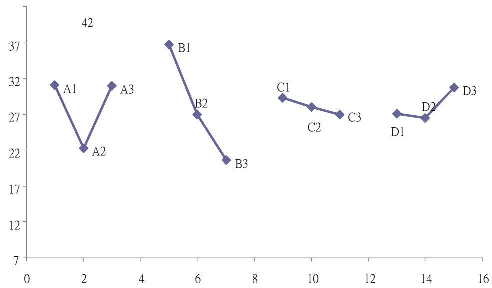

Fig 4.Optimum response diagram

TABLE 5 ROUGHNESS AUXILIARY TABLE

Sequence	A Diameter of Drill Bit	B Rotation Speed	C Power	D Feed Rate	Measured Data μm
1	1	4000	19	0.4	0.18
2	1	4500	20	1	0.2
3	1	5000	21	1.6	0.2
4	1.5	4000	19	0.4	0.18
5	1.5	4500	20	1	0.27
6	1.5	5000	21	1.6	0.15
7	2.3	4000	19	0.4	0.24
8	2.3	4500	20	1	0.23
9	2.3	5000	21	1.6	0.24

TABLE 6 ANOVA TABLE

Factors	1	2	3	DOF	SS	SMS	F	Contri-bution
Diameter	14.284	14.248	12.52	2	6.109	3.055	0.615	29.921
Rotation Speed	14.062	12.706	14.28	2	4.380	2.190	0.441	21.451
Power	14.713	13.757	12.58	2	6.830	3.415	0.688	33.45
Feed Rate	12.888	14.284	13.88	2	3.099	1.549	0.312	15.178

2) Roughness Analysis

According to the results of boring data, the relationship and framework on surface roughness and boring parameters are discussed for getting the optimum boring parameter combined with the minimum roughness of ceramic materials. The surface roughness experiment employs the STB (smaller the better) characteristics for S/N ratio and plots the results as shown in Table 5 and Fig.5. The contribution of every factor on roughness is shown in Table 6.

This research deals with boring and machining of ceramic materials, with drill diameter, rotation speed, power and feed rate of different cuttings, as well as fixed diamond tool particle number (#320) and diamond particle diameter (36μ~54μ), if the diameter is the same, the larger the feed rate, power and rotation speed are, the larger the roughness is. As presented in Table 5, there is a small roughness (0.15μm) with the drill diameter (ψ1.5), the rotation speed (5000RPM), the power (21) and the feed rate (1.6). Or with the different drill diameters (ψ1.0, ψ1.5) and the same rotation speed (4000RPM), power (19) and feed rate (0.4), the roughness is sub-low (0.18μm). Thus, for a fixed diameter of drill (ψ1.5), the larger feed rate, power and rotation speed have still a lower roughness, as shown in Table 5.

As for the analysis of variance (ANOVA), we can obtain an objective judgment about the relative effect of different factors to roughness. As shown in Table 6, it is the ANOVA about the relative effect of different factors to roughness. In addition, it usually employs F statistic ($F = s_1^2/s_2^2$) to denote the relation of factors effect on error deviation. The larger F statistic is, the more important to the effect of roughness the factor is. The results can obtain from the Table 6. To think of the contribution, the factors' order of importance on roughness is in the order as: power＞ drill diameter＞ rotation speed＞ feed rate.

The reason to cause the effect is stated as above. Under the experiment condition, with the different drill diameters (ψ1.0, ψ1.5) and the same rotation speed (4000), power (19) and feed rate (0.4), the roughness is sub-low (0.18μm). So, we can induce that the lower rotation speed, power, and feed rate, the smaller roughness is. The diamond particles of tools with a fixed drill diameter are the same, so when the roughness is considered only, in the scope of this experimental configuration table, the increase of rotation speed provides higher probability for diamond particle to contact, grind and machining workpieces. Also, when the diameter of drill for boring is larger, the higher probability exists for inner hole

wall to contact, grind and machining workpieces. The probability of contact increases with the size of drill diameter. Consequently, the impacts of power, drill diameter and rotation speed are higher than that of feed rate. Some experimental results [9,10,11] had shown that a better surface morphology and less sub-surface damage was obtained using smaller grind size and lower feed rate. That is, using bigger size drill and larger feed rate will cause more surface damage.

According to parameters configuration and experimental results (shown as Table 2 and Table 5), with diameter of drill (ψ1.5), power (21), rotation speed(5000), and feed rate (1.6), we can induce that fixed diameter with larger feed rate, power and rotation speed can get lower roughness(0.15μm).

To discuss roughness of ceramic materials after machining only, we must consider the impacts of other related parameters as well as the same diameter. In Fig. 5, we obtain the most appropriate machining parameter A3B2C3D1 of the optimum response diagram. This indicates that diameter of drill (ψ2.3), rotation speed (4500), power (21), and feed rate (0.4) can get better roughness within the experimental configuration (as shown in Table 2).

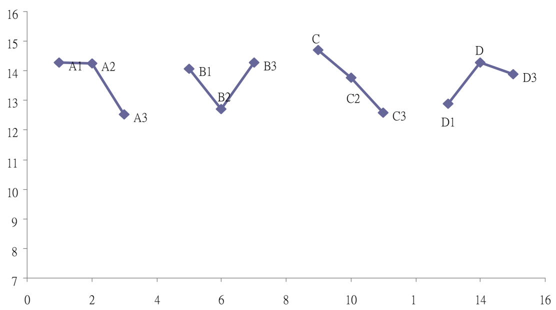

Fig. 5 Optimum response diagram

III. CONCLUSION

This paper uses RUM to establish relationship mode of surface quality of drill hole wall on ceramic materials, and utilizes such mode to find out drilling parameters and tool geometry of optimal hole wall surface quality for study on drill hole quality. The following conclusions may be drawn based on experimental results above:

1. Relational equation of drill hole wall surface quality and drilling parameters and tool geometry may be used to forecast hole wall quality.

To consider the range of experiment factors as shown in Table 2, when diameter of drill is fixed (ψ1. 5), we can find out greater MRR (0.19154 mm^3/min) with larger rotation speed, power and feed rate as the results shown in Table 3.

2. In range of this experiment (Table 2), under the conditions of greater rotation speed, power and feed rate as well as fixed diameter (ψ1.5), lower roughness (0.15μm) can be obtained. This results show as in Table 5.

3. The observation is carried out according to influence analysis chart of hole deviation, and steady cutting being performed at the same intervals; i.e. under stable action of all parameters, optimal roughness and greater removal rate can be obtained.

Experimental planning based on OA of Taguchi Method has both advantages and disadvantages as follows: (1) arranging the least number of experiments to attain the best experiment efficiency; (2) simple and quick analysis; (3) being not capable of analyzing multiple objective function.

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REFERENCES

[1]. Keizo Sakuma, Koichi Taguchi, and Akio Katsuki, "Study on Deep-Hole Boring by BTA System Solid Boring Tool--Behavior of Tool and Its Effects on Profile of Machined Hole", Bull. Japan Soc. of Prec. Eng, Vol. 14 No.3 143-148, 1980.

[2]. Y. B. Gessesse, V. N. Latinovic, and M. O. M. Osman, "On the Problem of Spiralling in BTA Deep-Hole Machining", Journal of Engineering for Industry, Vol. 116 161-165, 1994.

[3]. Akio Katsuki, Hiromichi Onikura, Keizo Sakuma, Torin Chen, and Yukitaka Murakami, "The Influence of Workpiece Geometry on Axial Hole Deviation in Deep Drilling", JSME International Journal Series III, Vol. 35 No. 1160-167, 199

[4]. M. M. EI-Khabeery, S.M. Saleh, and M. R. Ramadan, "Some Observations of Surface Integrity of Deep Drilling Holes", Wear. 142 331-349, 1990.

[5]. J. Frazao, S. Chandrashekhar, M. O. M. Osman, and T. S. Sankar, "On the Design and Development of a New BTA Tool to Increase Productivity and Workpiece Accuracy in Deep Hole Machining", The International Journal of Advanced Manufacturing Technology, 1. (4) 3-23, 1986.

[6]. N. Latinovic and M. O. M. Osman, "Optimal Design of BTA Deep-Hole Cutting Tools with Staggered Cutters", INT. J. PROD. RES. VOL. 27 NO. 1, 153-173, 1989.

[7]. Gilmore R., Ultrasonic machining of ceramics, SME Paper, MS90-346,1990.

[8]. Rozennberg L.D., Kazantsev V.F. et al., Ultrasonic cutting, Consultants Bureau, NewYork,1964.

[9]. Kohls J.B., Ultrasonic manufacturing process: Ultrasonic machining (USM) and ultrasonic impact grinding (USIG).The Carbide and Tool J., 1984, 16 (5), 12-15.

[10]. Haslehurst M., Manufacturing technology (3rd edn.), 1981, pp.270-271.

[11]. Soundararajan, V. and Radhakrishnan V., An experimental investigation on the basic mechanisms involved in ultrasonic machining. Int. J.MTDR, 1986, 26 (3), 307-321.